Pulse Power Modeling and Analysis For Electromagnetic Accelerator Design

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Abstract. This paper models a pulse forming network consisting of series of high voltage energy storage capacitors and inductors. These accumulate electrical energy over a comparatively long time, and then release the stored energy in the form of a relatively square pulse of comparatively short duration for pulsed power application. As railguns move from basic research of the electromagnetic acceleration technology to the development of systems for specific applications, a wide variety of power supply and railgun systems is being investigated. The problem with most of the research work on improvement of railgun system for efficient acceleration of masses to impressive velocities centers on how to provide the primary energy store, and how to make the armature current more nearly constant with time during the entire shot period. This has not been solved till date. This paper provides a simplified and enhanced model for pulse power storage and transfer. The model is made up of 30 capacitors arranged into 6 sub- banks. Each of the sub-banks has five capacitors of the same ratings connected in series for voltage maximization. The capacitor banks are linked in parallel with an inductor connected across the sub-banks. Each section of the bank is charged 2000V. The resulting pulse power discharge is a square wave with 258µs pulse duration and the 2000V initial condition results in a 1000V, 20000A (20kA) square pulse into the 49mΩ load resistor that represents the power device. The transferred energy of the network is 5.2kJ and the pulse power delivered by the model is 20MW.
Keywords: pulse network, pulse current, pulse power, electromagnetic accelerators, railgun.

1 INTRODUCTION

Pulsed power is the term used to describe the science and technology of accumulating energy over a relatively long period of time and releasing it very quickly thus increasing the instantaneous power. By releasing the stored energy over a very short interval (a process that is called energy compression), a huge amount of peak power can be delivered to a load. Examples where pulsed power technology is commonly used include radar, particle accelerators, ultra strong magnetic fields, fusion research, electromagnetic pulses, high power pulsed lasers, electromagnetic forming, Marx generators, electromagnetic accelerators (railguns and coilgun) and flash tubes. Users of pulse discharge networks are concerned with efficient energy delivery from the capacitor network to the load.

Some of the preliminary research that was conducted at the Center for Electromechanics (CEM), University of Texas, Austin and in some other places on railgun design using pulse forming network (PFN) shows that limited number of meshes (a combination of primary energy store and an inductor) used in the pulse forming network topology could not produce a better smooth current pulse. The ripples on the pulse current curve have a limiting effect on the effective current that determines the launch velocity.

This research work centers on the application of capacitors in pulse power network design to produce specific energy for use in electromagnetic accelerator design. The objective of this research is to use PSpice simulation software to model a pulse power network using parameters of capacitors found around my environment. And to analyze the pulse current and power generated from the model based on the underlying theories.

Effective Charging Circuit Parameters

The circuit schematic for the resistive (RC) charging case is shown in figure 1. In this specific model, the capacitor (initial condition = 0 volts) is charged from a 1000 V power supply. A 1000 ohm series resistor limits the charging current to 1A and the switch is closed at approximately time 0. With the 1000 ohm resistor and the 1 uF capacitor, the time constant for the circuit is 1 mS.

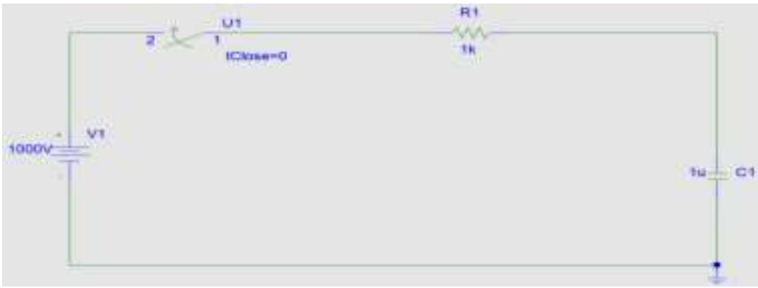

Fig. 1.RC Circuit model for charging a capacitor

In the graph shown in figure 2, V (C1) is the voltage on the 1uF capacitor as it charges up. The circuit current, I(C1), is displayed in figure 3.

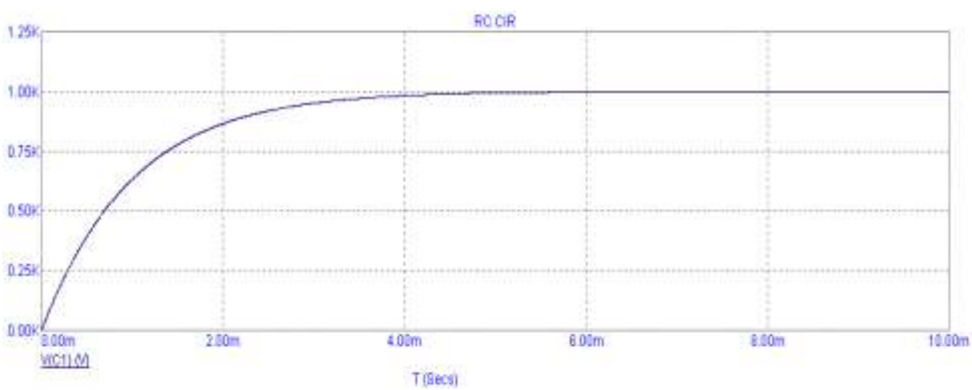

Fig. 2. Graph showing exponential voltage build-up in a charging capacitor (V(C1)).

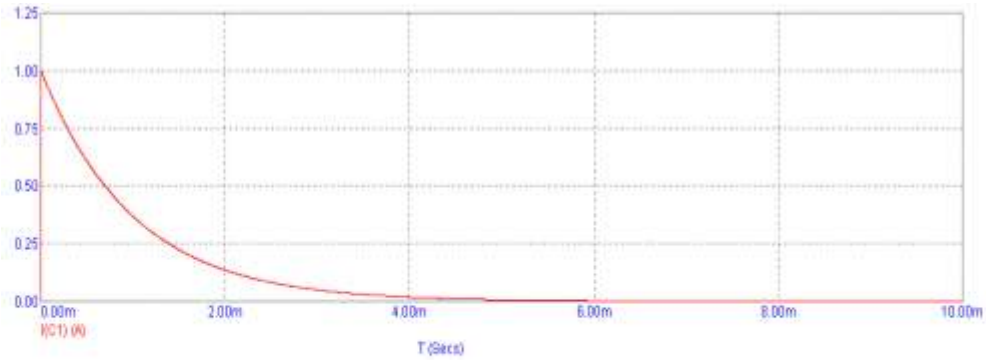

Fig. 3. Graph showing exponential current decay in a charging capacitor (I(C1)).

Figure 4 shows the graph of energy stored in the capacitor, ES(C1), and the energy dissipated in the charging resistor, ED(R1). One can see that by the time the capacitor is fully charged, the energy stored is equal to the energy dissipated (the charging is only 50% efficient). Because of this limitation, the circuits for pulse power applications are charged with more efficient components.

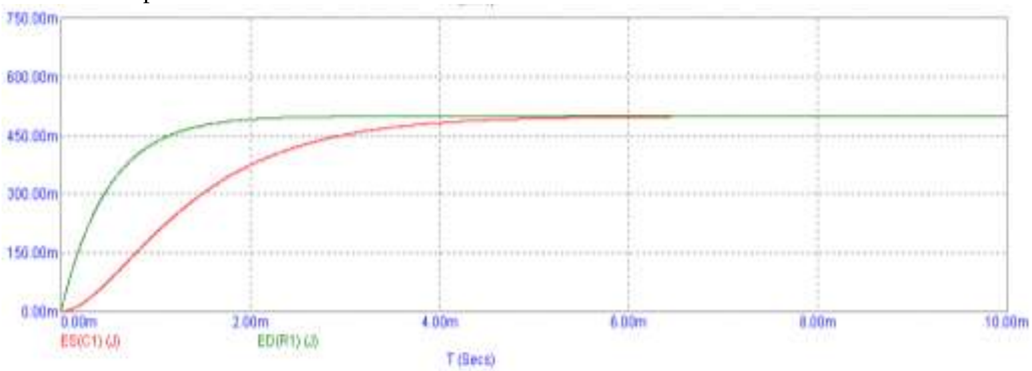

Fig. 4. Graph of energy stored and energy dissipated in a resistive charging circuit.

The charging element can be either a resistance or an inductance. A resistance in series with the energy-storage capacitor of a voltage-fed network and the power supply is a simple method of presenting energy accumulation and storage but the inherent efficiency of such an arrangement is well known to be never greater than 50 per. The graph of energy stored and energy dissipated in a resistive charging circuit in figure 4 shows that much of the energy is lost in the circuit resistor.

The use of an inductance as the charging element, however, makes it possible to design the charging circuit for a very high efficiency. As a result, inductance charging has been used almost exclusively in pulse power design. If the resistance of the charging inductor is neglected, that is, if there are no circuit losses, the final network voltages is always equal to 2Vs, regardless of the value of the inductance chosen. Practical circuits always have losses, however, but if the quality factor of the circuit is high, the ratio of network to power-supply voltage is only slightly less than two, and is not greatly affected by the actual value of inductance that is used. If the RC Circuit model for charging a capacitor in figure 1 is modified, whereby the resistor R = 1k is replaced by an inductor of 10uH, the final network voltage of the inductive charging circuit will be as shown in figure 5. Which is 2.0kV as against the 1kV achieved using resistive charging circuit.

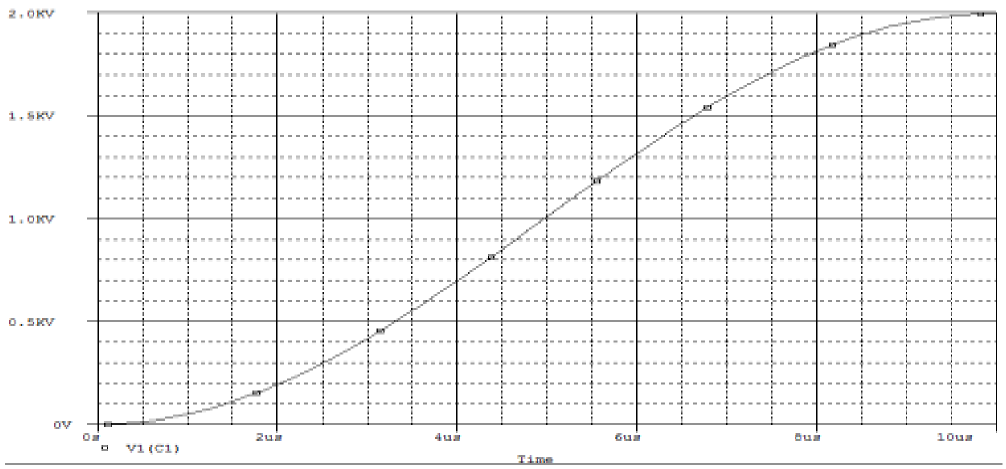

Fig. 5. Graph showing final network voltage of the inductive charging circuit.

PULSE FORMING NETWORK (PFN) TECHNOLOGY.

A PFN consists of a series of high voltage energy storage capacitors and inductors. These components are interconnected (as a "ladder network") that behaves similarly to a length of transmission line. Sometimes an actual length of transmission line is used as the pulse forming network. A charged lossless transmission line produces a rectangular pulse of energy if it is connected through an ideal switch to a pure resistance equal in magnitude to the characteristic impedance of the line. This can give substantially flat topped pulses at the inconvenience of using a large length of cable. However, electrical energy can be stored within the charged capacitors of the PFN. For this reason, a PFN is sometimes called an "artificial, or synthetic, transmission line". The PFN upon command, a high voltage switch transfers the energy stored within the PFN into the load and the network of capacitors and inductors within the PFN creates an approximately square output pulse of short duration and high power. This high power pulse becomes a brief source of high power to the load . A common form of PFN used in Pulse power application is the Guillemin Type E network, in which the capacitance is the same in each mesh and there is mutual inductance between adjacent coils. The squareness of the output pulse is a function of the number of meshes. If the characteristic impedance of the PFN is matched to that of the load, the energy will be almost completely dissipated in the load (no reflection), and the voltage across the load will be one-half the charge voltage of the PFN capacitors.

Typically the inductor closest to the load is made larger than the other inductors. This is done to prevent overshoot. This inductor is ~30% larger than the other inductors. The nominal capacitance and inductance per mesh are simply the totals divided by the number of meshes. Adjustment of the mutual inductance between meshes and the precise values of the first and last mesh inductances are used to "tune" the network for optimum performance. Sometimes the inductors are wound on a continuous form. Optimum wave shape is typically obtained with about 15% mutual coupling between inductors in the PFN. This type of PFN is known as a Type E PFN. However, there are many topologies that can be used to form a PFN.

Pulse Power, Power Transfer, And Network Load

Consider the circuit in which the switch can be clossed instantly and is assumed to have zero resistance when clossed. If the line is charged to a potential V_0, the current in the load after closing the switch is given by :

$$i_l(t) = \frac{V_0}{Z_0+R_l}\{1-U(t-2\delta) - \frac{Z_0-R_l}{Z_0+R_l}[U(t-2\delta) - U(t-4\delta)] + (\frac{Z_0-R_l}{Z_0+R_l})^2[U(t-4\delta) - U(t-6\delta)]\}$$

(1)

Where U (Δt) = 1 for $\Delta t > 0$,

U (Δt) = 0 for $\Delta t < 0$,

(Δt) = (t-n δ), n = 2, 4, 6 …

In general, only the energy transferred to the load during the first time interval 2δ is of practical value, and in that case,

$$I_l = V_0 \frac{1}{R_l + Z_0} \qquad (2)$$

and

$$V_l = V_0 \frac{R_l}{R_l + Z_0}$$

(3)

The pulse power in the load is

$$P_l = V_l I_l = \frac{V_0^2}{(R_l + Z_0)^2} R_l,$$

(4)

And the energy dissipated in the load is

$$W_l = P_l \tau = \frac{V_0^2}{(R_l + Z_0)^2} R_l \tau \qquad (5)$$

Where $\tau = 2\delta$ is the duration of the pulse at the load. From the foregoing equations, the pulse power and the energy dissipated in the load per pulse are a function of the load resistance. The value of load resistance for maximum power transfer can be obtained by differentiation of Equat.4

$$\frac{dP_l}{dR_l} = \frac{V_0^2}{(R_l + Z_0)^2} - \frac{2V_0^2 R_l}{(R_l + Z_0)^3} = 0 \qquad (6)$$

And the maximum power transfer is obtained when

$$R_l = Z_0 \qquad (7)$$

With this condition,

$$I_l = \frac{V_0}{2Z_0}, \qquad (8)$$

$$V_l = \frac{V_0}{2}, \qquad (9)$$

$$P_l = \frac{V_0^2}{4Z_0} \qquad (10)$$

and

$$W_l = \frac{V_0^2}{4Z_0}\tau \qquad (11)$$

If the load impedance equals the line impedance, there are no reflections and all the energy stored in the line is dissipated in the load during the interval 2δ. Any mismatch causes part of the energy to be dissipated to the load after the time 2δ, and thus results in a decrease in power during the main pulse. Exact matching of the load to the transmission line impedance is not particularly critical from the standpoint of power transfer as long as the mismatch does not exceed 20 to 30 per cent by taking the ratio of the power into any load resistance R_l to the power into a matched load Z_0.

The energy dissipated in the load under matched condition is equal to the energy stored in the transmission line capacitance before the pulse, or

$$\frac{V_0^2}{4Z_0}\tau = \frac{1}{2}C_0V_0^2$$

(12)

which gives the fundamental relation

$$\tau = 2C_0Z_0 \qquad (13)$$

$$C_0 = \tau/2Z_0 \qquad (14)$$

In practical circuits the load current is reduced by the losses in the circuit, V_0 and Z_0 are equivalent to V_N and Z_N respectively (the subscript zero refers to lossless transmission lines and the subscript N to actual networks).

PULSE FORMING NETWORK ANALYSIS AND PULSE CURRENT GENERATION

An array of equal inductors and capacitors are used to approximate a transmission line with discrete elements. The component values are optimized to synthesize a pulse output with minimum flat top ripple. Pulse Forming Networks with fewer sections can also be designed although they would typically generate more pulse ripple and longer pulse risetimes/falltimes. Conversely, more PFN sections can be designed to reduce the pulse ripple and the rise/fall times of the output pulse. Since PFNs approximate a transmission line, they must be charged up to twice the desired output pulse voltage since half the voltage is dropped across the PFN impedance and the remainder across the load impedance.

For the design of this system, Rayleigh Line pulse forming network method was used for its simplicity and its consistent capacitances and inductances, therefore reducing the overall complexity of the system. When designing the Capacitor bank, the choice of capacitors was based on ones that could be found around. One is 2200 uF, 400V Electrolytic capacitors and the other 15000uf, 100V capacitor. In this design the 2200uF, 400V were used because of the relatively better voltage rating which will be harnessed in the Pulse Forming Network to produce better current pulse. Getting this allowed for a 5 kJ capacitor bank, totaling 30 capacitors. These capacitors were arranged evenly to make 6 banks of capacitors. Each bank has five capacitors in series at total capacitance of 440uF, 2000V and 880J. That is:

PE = ½CV^2

$= \frac{1}{2}$ x 440 x 10^{-6} x $(2000)^2$

= 880J of energy per bank.

The banks were connected in parallel. This set up was designed to eliminate Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL), and maximize both voltage and capacitance.

The model pulse network was designed using PSpice 9.1 and the pulse current output that will serve as input to an Electromagnetic Accelerator was determined. The pulse network uses banks of capacitors separated by inductors that delay the output of the individual banks so that a combined resultant output pulse power will be generated. The circuit arrangement is as shown in figure 6.

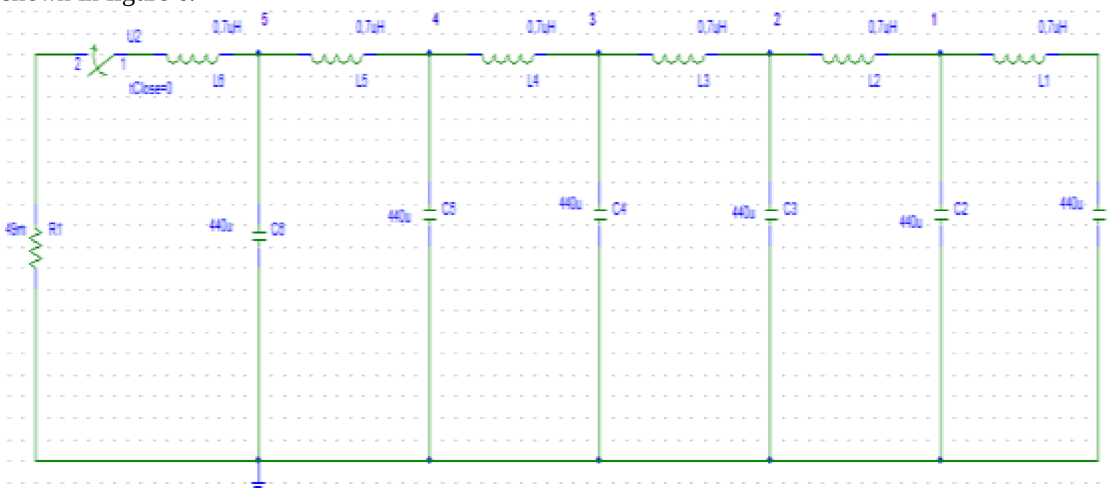

Fig. 6. Pulse Forming Network schematic at 49mΩ load impedance

Each section of the bank is charged to 2000V. Using PSpice Simulation Software to analyze the circuit, the resulting pulse power discharge produced a square wave at 258uS pulse duration and the 2000V initial condition results in a 1000V, 20kA (20,000A) square pulse into the 49m ohm load. The generated pulse currents and voltages from the different capacitor banks and the resultant current and voltage transferred to the load are displayed in figures 7, 8, and 9.

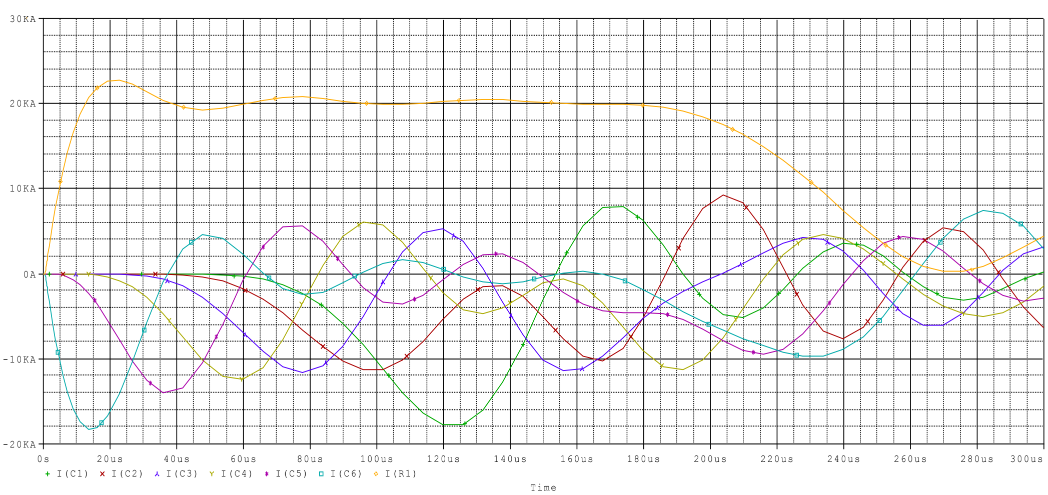

Fig.7. The output pulse current from Capacitor Bank C1, C2, C3, C4, C5, C6 and the resultant pulse current transferred to the load (R1) at 258uS pulse duration. The resultant current pulse at the load is 20kA (20000A).

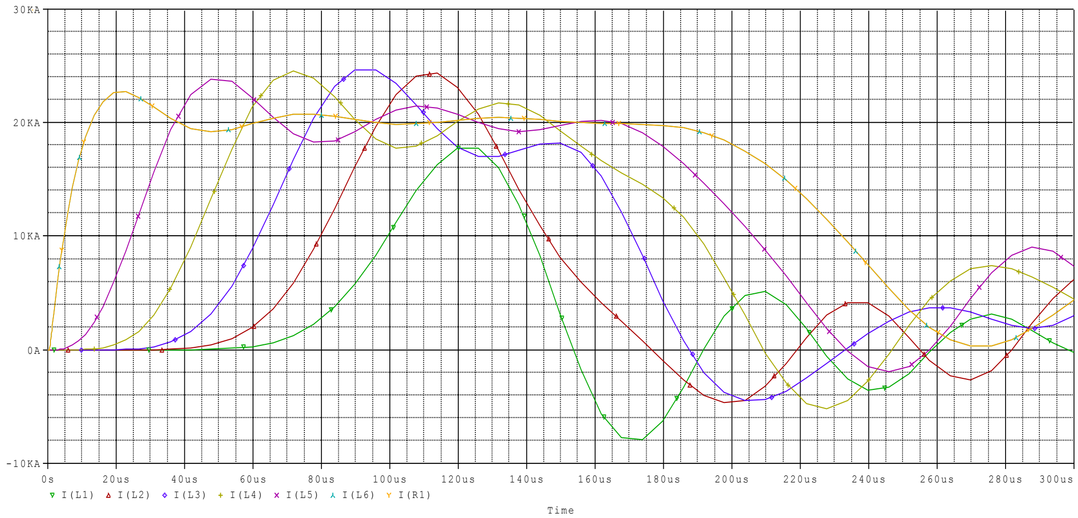

Fig. 8. The delayed output pulse current from inductors: L1, L2, L3, L4, L5, L6 and the resultant pulse current transferred to the load (R1) at 258uS pulse duration. The resultant current pulse at the load is 20kA (20000A).

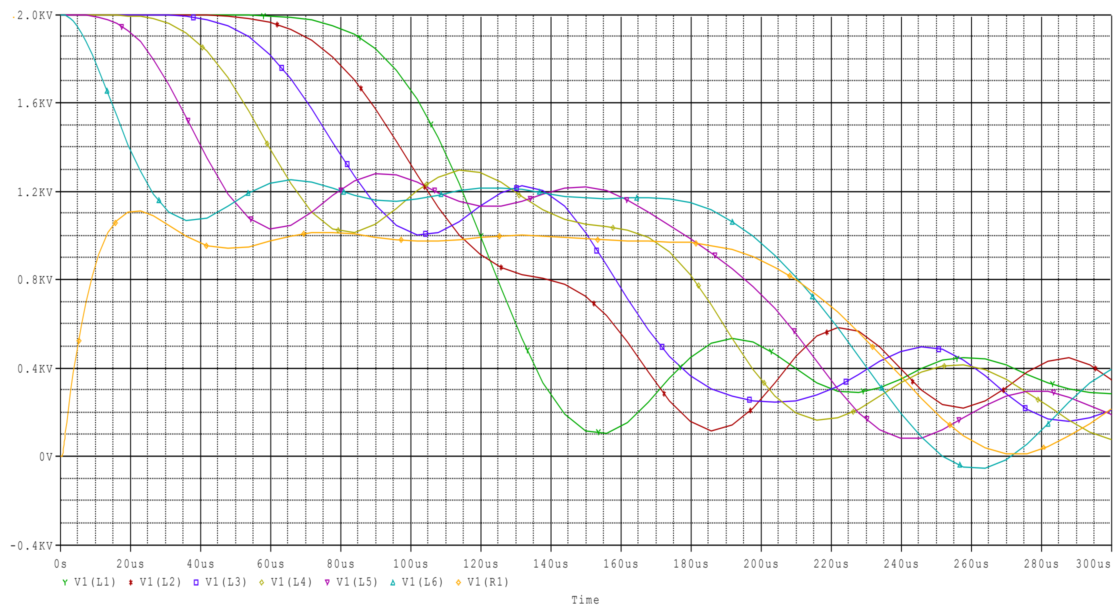

Fig. 9. The graph of the constituent capacitor bank voltages (2000V) and the resultant network voltage (1000V) that is available to the load (R1).

The Power and Energy delivered by the Pulse Forming Network

The energy stored in the network is equal to the energy dissipated in the load under matched condition:

$W_0 = \frac{1}{2} C_0 V_0^2 = \frac{V_0^2}{4Z_0} \tau_0$

V_0 = 2000V as display in the probe graph

$Z_0 = R_l$ = 49m Ohms as in the circuit schematic

$C_0 = \sum_{n=1}^{\infty} C_n$= 440 + 440 + 440 + 440 + 440 + 440 = $2640\mu F$

where:

τ (T) = $2C_0 Z_0$

Substituting for W_0 gives:

$W_N = \frac{1*2640*10^{-6}*2000^2}{2} = \frac{2000^2}{4*49*10^{-3}} * 2 * 2640 * 10^{-6} * 49 * 10^{-3}$
= 5280J = 5265J

If this energy is transferred to the load in 258microseconds, the peak power that will be delivered to the load is 20MW.

To calculate for the pulse duration $\tau = 2C_N Z_N$

$= 2 * 2640 * 10^{-6} * 49 * 10^{-3}$

= 258.7uS. (This can easily be read from the probe graph).

Where $R_l = Z_0 = \sqrt{\frac{L}{C}}$

CONCLUSION

The performance of the pulse forming network is the heart of the modulator for radar or electromagnetic accelerator operation. The energy so produced provides the force for the armature acceleration in the case of electromagnetic accelerators. However, pulse power design is determined by the pulse-power and energy-per-pulse requirements. The voltage-impedance relation in equation (10) shows that the output pulse power is proportional to the square of the voltage on the network and inversely proportional to the network impedance. Therefore at various impedances and voltages, minimum and maximum pulse power can be generated from an ideal pulse network. And if nearly matched condition is to be realized, then the voltage necessary to supply a high pulse power to a high impedance load becomes extremely high too. This analysis could be remodeled using capacitors with higher parameters ratings.

An improvement on number of meshes was adopted in the pulse forming network topology and this produced a better smooth current pulse. The ripples on the pulse current curve are minimized as shown on figure 7,8,9, and the limiting effect on the effective current has been removed.

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